Integrated Mining Impact Monitoring (EU-Project i^{2}Mon) for Open-pit and Underground Mines

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ABSTRACT:

Monitoring mining impact has become increasingly important as the awareness of safety and environmental protection is rising. Our project Integrated Mining Impact Monitoring (i^{2}Mon), funded by European Commission – Research Fund for Coal and Steel, intends to monitor the mining-induced impact, in particular, ground movement. The monitoring system comprises terrestrial measurement and remote sensing: levelling, GPS, LiDAR scanning, UAV survey, and SAR interferometry. The aim is to launch an interactive GIS-based platform as an early warning and decision making service for mining industry. This study has developed a scheme based on advanced SAR interferometry to monitor the ground movement over an extensive area at millimetre level. The first test site is a deactivated open-pit mine in Cottbus, Germany owned by Lausitz Energie Bergbau AG. The whole area was reclaimed into a post-mining lake and must be monitored for the safety. The second test site is located in Poland, where the underground mining operated by POLSKA GRUPA GÓRNICZA began in June 2021. We have monitored the in-situ ground movement carefully as part of the influenced area covers the human settlement. The ground movement of our test sites was analysed from Sentinel-1 images. The crucial parameters include stepwise movement series, instantaneous velocities and accelerations, and significance index. In addition, six corner reflectors along with sensors like GPS were installed across the region in Cottbus. They were observed in the Sentinel-1 series and the GPS readings will be used for validation. Finally, all the data will be integrated into DMT's platform – SAFEGUARD.

1. INTRODUCTION

For many countries, the mining industry accounts for an important component of their economy. An appropriate monitoring scheme is necessitated to legally activate, reactivate, or terminate mining operations. In general, open-pit and underground mining causes surface deformation like ground subsidence. Monitoring such a mining impact is increasingly important for the safety of human lives and properties. For example, the catastrophic dam failures in Mariana and Brumadinho, Brazil resulted in the loss of human lives (205 deaths and 122 missing persons) and countless property damage in 2015 and 2019, respectively. The investigation of the first disaster reveals there were signs of structural damage on the dam, which were earlier reported from the on-site measurement. The detail can be referred to https://en.wikipedia.org/wiki/Brumadinho_dam_disaster. We believe such a disaster could be prevented by implementing a reliable monitoring system.

Generally, a monitoring routine relies on in-situ surveys, which are considered reliable and accurate while expensive and time-consuming. Remote sensing based on spaceborne data offers an efficient and cost-effective alternative. This technique aims at a frequent surveillance over a large area and provides comparable complements to the in-situ measurement. The information derived from both sides will be jointly analysed for disaster prevention.

Our Integrated Mining Impact Monitoring (i^{2}Mon) project (funded by the European Commission – Research Fund for Coal and Steel) intends to develop a mining monitoring system to the public. The project website is http://www.i2monproject.eu/about-news/; the consortium includes DMT, EFTAS, TU Bergakademie Freiberg, IMG PAN, TU Delft, Mainz University of Applied Sciences, Airbus Defence and Space, LASERDATA, Lausitz Energie Bergbau AG (LEAG), and POLSKA GRUPA GÓRNICZA (PGG). The multi-source data come from geodetic and geotechnical devices (e.g., levelling and GPS), laser scanning, UAV survey, and multi-spectral and radar satellites (e.g., Sentinel-1/-2 and TerraSAR-X). They will be processed and combined to assess the mining impact. Among them, the movement phenomena are modelled to interpret the factors and physical processes at different spatiotemporal scales. The goal is to launch an interactive GIS-based platform as an early warning and decision making system for mining industry.

We (EFTAS) are contracted to lead work package 2 – Space and Airborne Remote Monitoring. This package is to develop a monitoring system based on advanced DInSAR (ADInSAR) processing of multi-temporal spaceborne SAR images. (Berardino et al., 2002; Crosetto et al., 2016; Ferretti et al., 2000, 2001, 2011; Hooper et al., 2004; Lanari et al., 2007). Spaceborne SAR delivers radar images, which are acquired regularly over a large area at a mission-oriented spatiotemporal resolution. Moreover, the active sensors are weather independent and have a day-and-night vision. This advantage makes SAR images free of cloud occlusion and always available for use. This system detects and analyses the mining-induced ground movement over an extensive area at millimetre level. Our results will be integrated with the data of other work packages.

Currently we have moved from preparation to real data tests. Section 2 describes our monitoring scheme and the relevant approaches. We then demonstrate our test results using Sentinel-1 images for open-pit and underground mines in Sections 3 and 4. Our works are finally concluded in Section 5 plus the future plan.

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2. MONITORING SCHEME

Our monitoring system (Figure 1) operates as a self-contained chain starting from image acquisition to product delivery. The complementary data, which are used here and there, contain ground truth, a priori knowledge, information from other sensor sources, and so on. The SAR images are downloaded and processed at a tailored period, e.g., every 6 days given Sentinel-1. The strategies and parameters are determined during the preparation to fulfill the requirementssuch as precision, accuracy, resolution, and coverage. Subsequently, we apply ADInSAR to evaluate the ground movement at the venue. The preliminary results are refined based on statistics and complementary data. The purpose is to improve the accuracy and precision. The resultant quality is checked during the analysis step. In addition, the physical parameters, e.g., time-series movement, velocity, and acceleration are derived via modelling. Afterwards, the informative and decisive products, e.g., a deformation or risk map, are generated for stakeholders and decision-makers. The results are also delivered into an integrated system DMT SAFEGUARD (Figure 2) under agreed data formats. Here various data, products, and information are jointly analysed to provide comprehensive knowledge in particular for disaster prevention. All procedures mentioned above operate fluidly in a semi-automatic way with the aid of specialists.

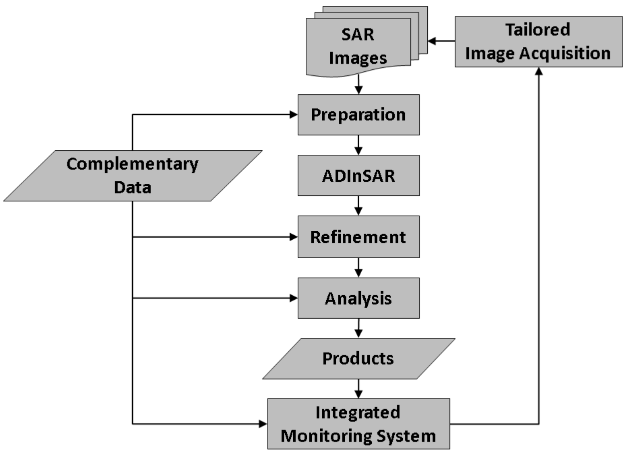

Figure 1. Monitoring scheme.

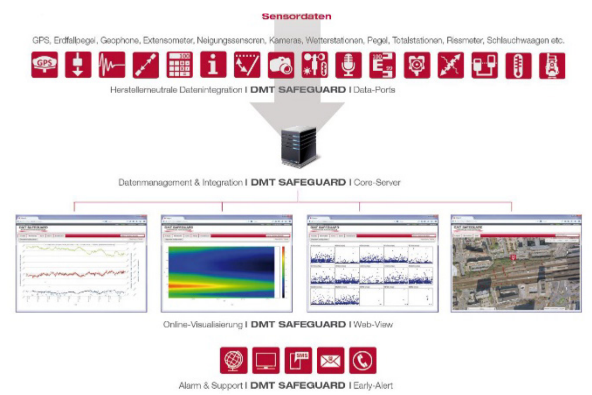

Figure 2. DMT SAFEGUARD – intergrated monitoring platform.

2.1 Spaceborne SAR images

The civil satellites are currently in operation using X, C, and L Bands. Three typical examples are TerraSAR-X, Sentinel-1, and PALSAR-2 (Table 1). Other operational and planned satellites include Capella (X), PAZ (X), COSMO-SkyMed (X), Radarsat-2 (C), RCM (C), SAOCOM (L), NISAR (L), and TanDEM-L (L).

In i[2]Mon we use Sentinel-1 images for test due to its versatile suitability. First, the use of C Band leads to a compromise result between X and L Bands. X Band is able to measure small deformation while the results suffer from coherence lose (accuracy degradation) especially over vegetation. In contrast, L Band is more robust against such a coherence loss; however, small deformation might not be detected. Mostly, C Band satisfies the requirement for a monitoring task. Second, a standard image package contains a large area (250 km × 200 km) thanks to TOPSAR acquisition mode. Such a large coverage enables a synchronous monitoring of multiple areas of interest. Third, the repeat cycle of 6 days empowers weekly monitoring. Last but not least, Sentinel-1 images are free of charge for both scientific and commercial uses.

Table 1. SAR data source.

Satellite	TerraSAR-X	Sentinel-1	PALSAR-2
Wavelength	X Band (3.1 cm)	C Band (5.6 cm)	L Band (22.9 cm)
Coverage Swath	5 ~ 260 km	250 ~ 400 km	25 ~ 350 km
Resolution	0.24 ~ 40 m	1.7 ~ 43 m	1 ~ 100 m
Repeat Cycle	11 days	6 days	14 days

In comparison, although TerraSAR-X images are not offered for free, their results are characterized by high-resolution details and more precise movement estimate. We will use them to inspect the detail if a hotspot featured by abnormal movement is discovered by Sentinel-1. If needed, we will turn to PALSAR-2, which is preferable if the area of interest is covered with dense vegetation.

2.2 Data processing

A bundle of tools: ENVI, SARscape, and IDL are used to build the main processing chain. ENVI is a specialized software of remote sensing developed under IDL environment. SARscape, mounted on ENVI as a module, deals with SAR interferometry, including basic image processing, ADInSAR processing, and analysis tools. IDL provides a platform to develop versatile functions. In addition, we also work with GMT, Python, GDAL, SketchUp, and ArcGIS to map and analyse our data. Finally, the results are outputted with specific formats compatible with the integrated monitoring platform.

Sentinel-1 images are downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/). Airbus is in charge of the access to TerraSAR-X. If PALSAR-2 images are required, they can be obtained from JAXA free of charge for a research proposal or purchased via authorized companies, e.g., Asia Air Survey. All deliveries will be shipped as a Single Look Complex (SLC) format and then imported into our processing chain.

Two ADInSAR techniques – Persistent Scatterer Interferometry (PSI) (Crosetto et al., 2016) and Small BAseline Subsets (SBAS) (Lanari et al., 2007) are considered in our monitoring system. Basically, they estimate the ground movement covering an extensive area at millimetre/year accuracy. PSI processes a time series of SAR images to detect target points of interest, which are characterized by coherent signals reflected from a ground patch of a certain size (dependent on image resolution). Such coherent signals are used to evaluate different forms of their movements, e.g., cumulative time series and mean velocity. The main limitation of PSI is that only few target points can be found from natural scenes like grass due to coherence loss. These natural scenes are commonly seen in mining regions. Similar to PSI, SBAS also uses multi-temporal SAR images to monitor ground movement. The difference is that SBAS is capable of detecting meaningful target points over natural areas, while the accuracy of movement estimation is a bit degraded compared with PSI.

2.3 Refinement and analysis

After a standard ADInSAR processing, the movement series are corrected based on a global median filtering to remove the systematic bias. Subsequently, they are calibrated by referring to a benchmark. If needed, we also apply a time-series filtering to remove residual noise. We will analyse the result qualitatively and quantitatively. For this purpose, relevant data are generated like amplitude map, coherence map, precision map, etc. The statistics from these data such as probability distribution are then examined. In addition, we also model the time-series movement of a single target point to further remove its noise and derive the physical parameters such as velocity and acceleration. In practice, we will customize this step according to the client's need.

3. TEST FOR OPEN-PIT MINE

The test site is located at the deactivating open-pit coal mine owned by LEAG in Cottbus, Germany. The 71 Sentinel-1 images are detailed in Figure 3. The mean velocity map (Figure 4) created by SBAS (Lanari et al., 2007) illustrates an overview of ground movement between 2018 and 2019. The mine is subject to different movement patterns. We also identified a significant ground uplift between the mine and city centre of Cottbus. To the west, the city seems quite stable without remarkable movement. These scenarios mentioned above have been validated by the experts in LEAG. Target points (TP) 1 – 4 were particular concerned by LEAG and so selected for further analysis in the following.

Mode	IW
Resolution	4.2 m × 13.9 m
Amount	71
Orbit	Ascending
Polarization	VV
Time Span	17.03.2018 – 17.05.2019

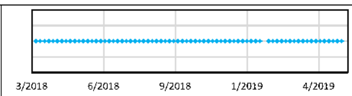

Figure 3. Sentinel-1 images used for test in open-pit mine in Cottbus, Germany (owned by LEAG).

The series of movement, velocity, and acceleration of TPs 1 – 4 are plotted in Figures 5, 6, and 7. TP 1 shows a continuous subsidence from the beginning to the end. The subsidence was speeding up in the first half and then slowing down to the end. Unlike TP 1, TP 2 was uplifting under a dynamic velocity. The uplift velocity kept restrained since the beginning but then bounced up after July 2018. After March 2019, the uplift was slowing down again. We also consider TP 3 uplifting while its extent and velocity variation are not comparable to TP 2. The time serie of TP 4 signifies a rather fixed object compared with other TPs. Indeed, it shows a bit uplift in the end but is regarded as insignificant.

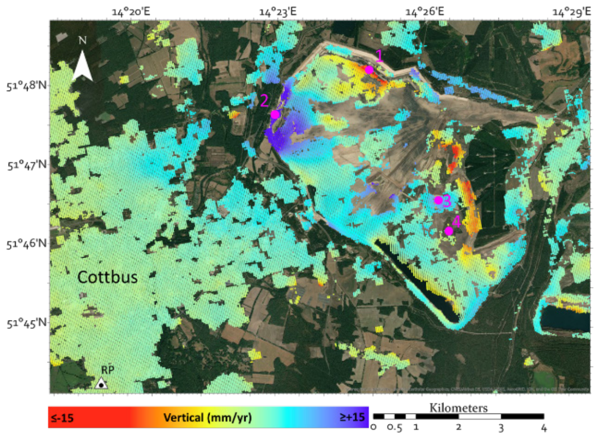

Figure 4. Mean vertical velocity map (17.03.2018 – 17.05.2019) in Cottbus, Germany. Top-right, open-pit mine owned by LEAG. Vertical movement converted from line-of-sight movement via trigonometry given no horizontal movement. Negative and positive, subsiding and uplifting. RP, reference point. Target points (TP) 1 – 4 selected for time-series analysis.

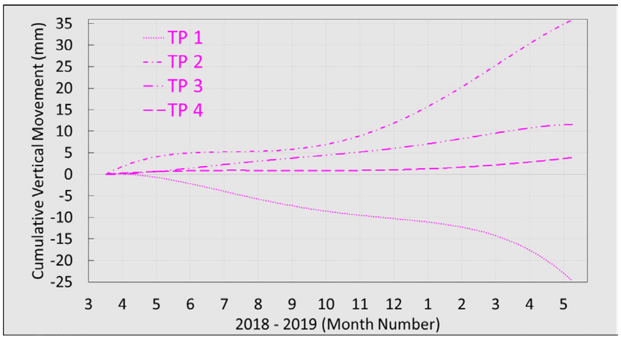

Figure 5. Movement series of TPs 1 – 4 (Figure 4)

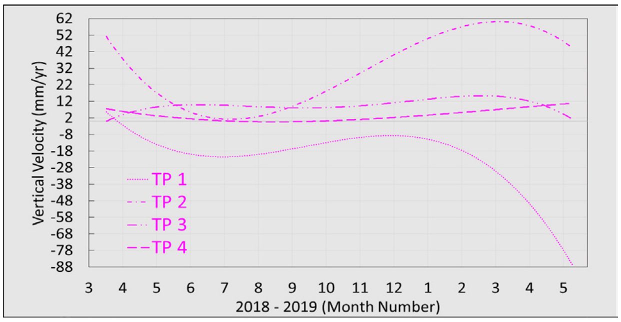

Figure 6. Velocity series of TPs 1 – 4 (Figure 4)

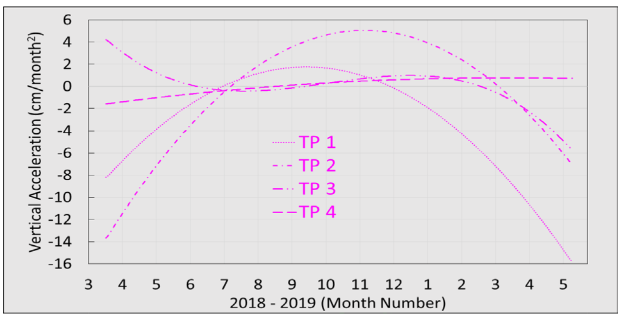

Figure 7. Acceleration series of TPs 1 – 4 (Figure 4)

A cluster analysis was done to extract the areas, which are subject to significant subsidence or uplift. For this purpose, Anselin local Moran's I (Anselin, 1995) was applied to the mean velocities

(Figure 4). The areas of significat movement are grouped and displayed in Figure 8. Most of the areas around the mine are labelled as uplift; some areas inside belong to subsidence. The region between the mine and city centre of Cottbus indicates an uplift trend. The movement is mainly credited with mining impact. The other factors are also considered, e.g., water table and elastic rebound. This cluster analysis helps us to identify hotspots for further investigation. If needed, we will use hydrological and geological data regarding water and soil to interpret the deformation in detail.

DMT and LEAG have deployed 6 corner reflectors along with sensors like GPS across the mine site in June, 2021. We will compare the GPS readings with our ADInSAR-derived ground movement in future. For preparation, we were looking for the signs of these CRs in the Sentinel-1 series (Figure 9). Their radar brigntnesses are presented by gamma naught (Small, 2011). Gamma naught is defined as the pure intensity of a complex signal reflected from ground. It can be interpreted as the calibrated radar brightness of an image pixel, which is independent from the local incidence. Overall, their brightnesses jumps remarkably in June and then maintain quite stably. This evidence indicates that the CRs are observable via the Sentinel-1 images. However, the brigntnesses for CRs 3 and 4 were down at some time points after June. The reason could be heavy rain or adjustment of CR.

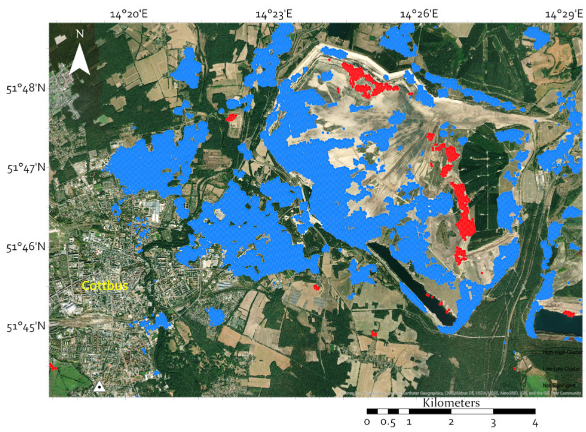

Figure 8. Cluster analysis of mean velocity (Figure 4). Red, significant subsidence; blue, significant uplift.

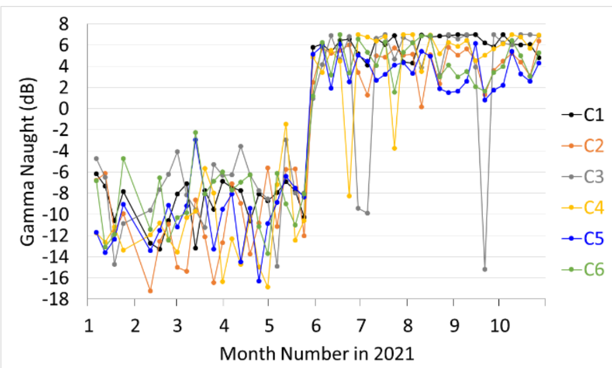

Figure 9. Series of gamma naught (i.e., radar brightness) reflected from 6 corner reflectors (C1 – C6) across open-pit mine owned by LEAG in Cottbus, Germany.

4. TEST FOR UNDERGROUND MINE

Our second test site is an underground mine in Lędziny, Poland (Figure 10). The mining activity, operated by PGG, has started in June, 2021. The mining started in region 501, followed by 502 and then 503. These regions cover partially the human settlement especially in the South. We assume that the mining impact has caused an extensive ground movement in the test site.. Our priority is to estimate the movement extent and to evaluate the risk of causing damages. For this purpose, the Sentinel-1 images of double orbits were used in ADInSAR (Figure 11); we merged their results to obtain more precise vertical and east-west movement components (Czikhardt et al., 2017; Samieie-Esfahany et al., 2010).

The mean vertical velocity map (Figure 12) reveals a quite strong subsidence around the venue especially in the residence region (around P1). We have informed our partners DMT and PGG to closely survey this region as a hotspot; the survey campaign including levelling and GPS was planned and should deliver the first result in early 2022. P1 in the hotspot is selected for the point-based analysis – time series of cumulative vertical movement (Figure 13) and of instataneous vertical velocity (Figure 14). The strong subsidence started since the mining and then slowed down. To be more specific, the subsidence was speeding up at first and then slowing down in early September due to bounce (Figure 14).

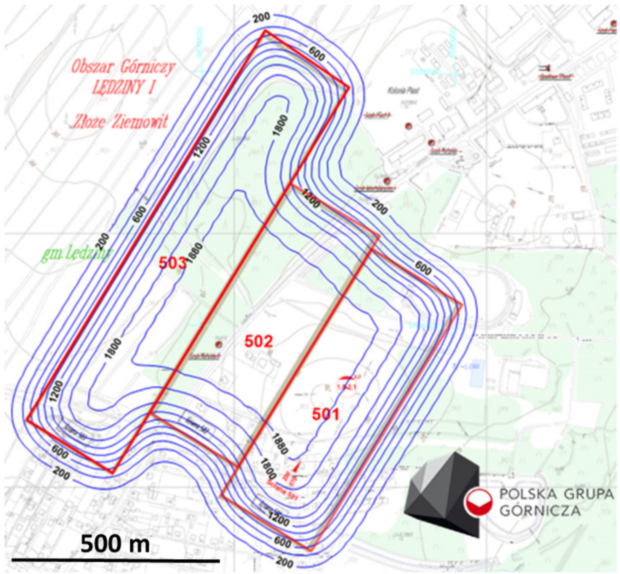

Figure 10. Underground mining, operated by PGG, in Lędziny, Poland. Mining begun in area 501 since June, 2021, followed by 502 and then 503.

Orbit	Amount	Mode	Polarization	Resolution
Descending	50	IW	VV	5 m × 15 m
Ascending	51			

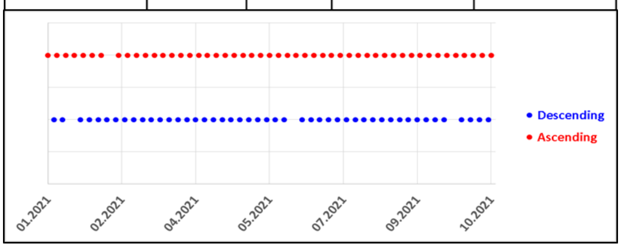

Figure 11. Ascending and descending Sentinel-1 images used for test in underground mine in Lędziny, Poland (owned by PGG).

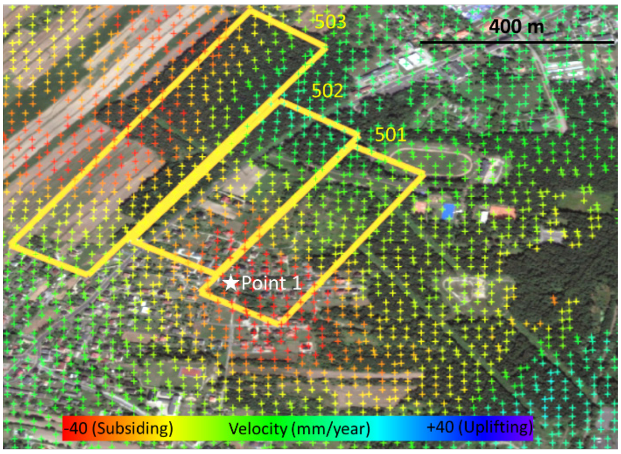

Figure 12. Mean vertical velocity map (January – October, 2021) subject to underground mining in Lędziny, Poland (Figure 10). Three mining regions: 501, 502, and 503. P1 for point-based analysis in Figures 13 and 14.

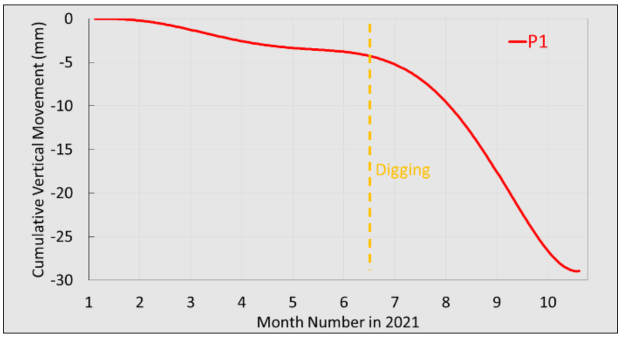

Figure 13. Cumulative vertical movement of P1 (Figure 12). Mining occurred in middle June.

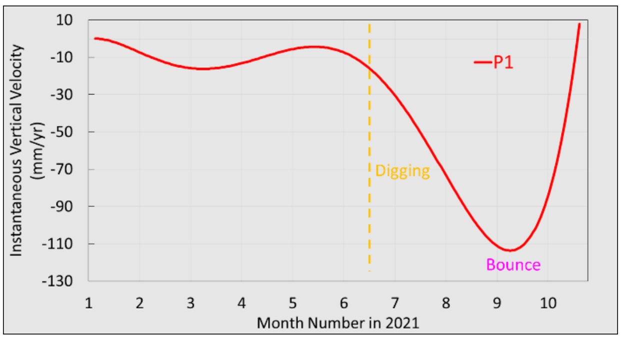

Figure 14. Series of instataneous vertical velocity of P1 (Figure 12). Mining occurred in middle June.

From Figure 15 we observe that the east-west movement is directed towards the centre of the mining acivity. The junction converges across regions 501 and 502. Such a subsidence bowl is typically subject to an underground mining. We selected P1 and P2 to analyse their time series of cumulative vertical movement (Figure 16) and of instantaneous vertical velocity (Figure 17). They were moving in a reverse direction since the mining. Both movements were then slowing down due to bounce same as the vertical movement (Figure 14). This mirroring of movement between P1 and P2 confirms again the bowl subsidence.

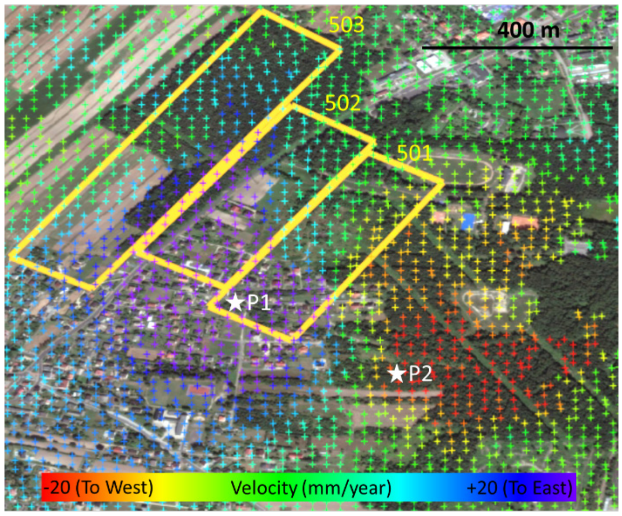

Figure 15. Mean east-west velocity map (January – October, 2021) subject to underground mining in Lędziny, Poland (Figure 10). Three mining regions: 501, 502, and 503. P1 and P2 for point-based analysis in Figure 16.

According to the vertical and east-west movement (Figure 12 to Figure 17), we infer that the bowl subsidence has relieved and so less likely cause damages, e.g., building collapse. We have created a significance map (Figure 18) by considering the range and autocorrelation of vertical and east-west movement. The significant movement (towards red) should be carefully checked in situ. Therefore, we will pay more attention on the residence area in the red circle because the movement is quite relevant. Later, a more precise report will be released by DMT and PGG based on in-situ measurement and investigation. The content contains accurate local movement and assessment of structural damage.

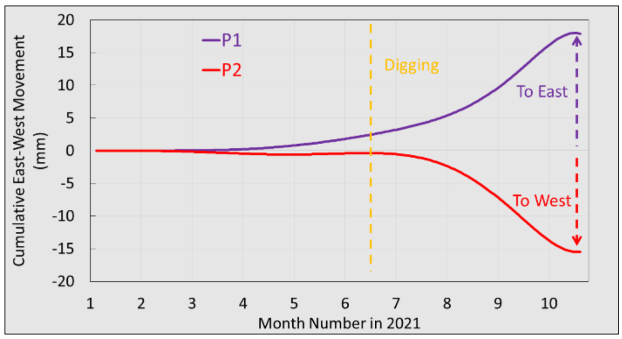

Figure 16. Cumulative east-west movement of P1 and P2 (Figure 15). Mining occurred in middle June.

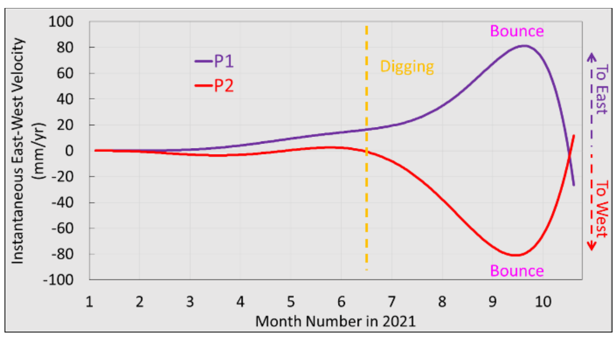

Figure 17. Series of instataneous vertical velocity of P1 and P2 (Figure 15). Mining occurred in middle June.

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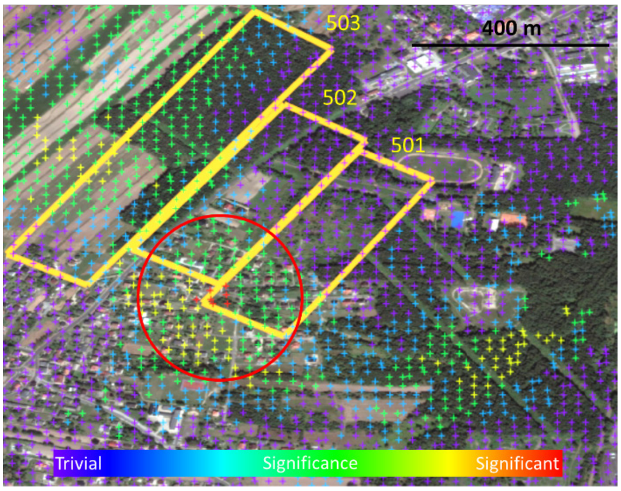
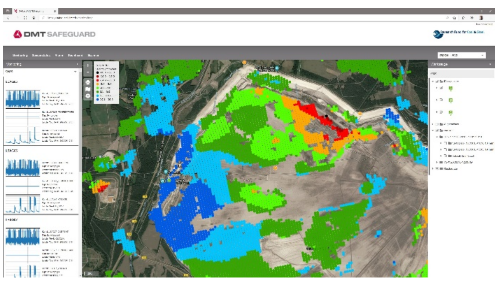


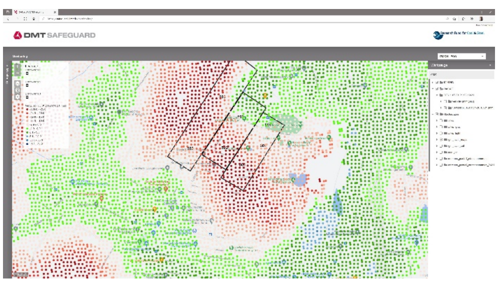
Figure 18. Movement significance map. Red circle, hotspot with high significance.

5. CONCLUSIONS AND FUTURE WORKS

This paper describes our results regarding work package 2 – Space and Airborne Remote Monitoring in i[2]Mon. We have analysed the ground movement by using ADInSAR for the open-pit mine in Cottbus, Germany and the underground mine in Lędziny, Poland. Here only costless Sentinel-1 images were used as a single source to derive the movement. Our results have pointed out some hotspots, which will be closely inspected using ground sensors like GPS and Levelling. In future, we plan a test using Capella constellation, whose InSAR mode will be available in 2022. Capella is capable of delivering VHR SAR imagery over a venue after an order request is placed in 4 hours on average; it will then take 1 hours until the second delivery; afterwards, the following delivery needs 2 hours each. The delivery time will be further shortened in future with improved processing capabilities and expansion of the satellite constellation. The quality and very high resolution of Capella empower us to inspect the ground detail. Finally, we will test our integrated monitoring system DMT SAFEGUARD.



Appendix A: DMT SAFEGUARD under construction. Example from open-pit mine in Cottbus, Germany owned by LEAG.



Appendix B: DMT SAFEGUARD under construction. Example from underground mine in Lędziny, Poland owned by PGG.

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